Influences of Age and Experience with Stepping Activities on Gait Adaptation During a Complex Walking Task

A thesis

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I’d like to thank everyone who let me postpone my academic responsibilities to go surfing when the waves were good.

ABSTRACT

The human gait is a biomechanically and neuromechanically complex task that requires coordination of all limbs and their respective degrees of freedom. Humans frequently face perturbations in their gait or walking environment, and how they adapt to these circumstances can differ depending on a variety of factors. Here, we examine how age, gender, and experience with stepping and balancing activities affect adaptation parameters during a complex walking task. We used a split-belt treadmill to contrive a novel walking task where each foot was moving at a unique velocity to induce a repeated, predictable demand in the walking environment. We measured joint angles, step times, and forces for three experimental phases: baseline, adaptation, and washout. We compared adapted variables to baseline variables to determine how individuals adapted their gait, how much they adapted, and when they adapted. Our results suggest that 1) experience with stepping activities could predict the horizontal and vertical forces generated while adapting, 2) age-related changes in gait variables are mitigated by stepping activities, and 3) gender can be used as a predictor of adaptation techniques. In addition to these primary results, we also were able to conclude that shoe-mounted inertial measurement units are a viable option for gathering data on step times and yield comparable results to those gathered via force treadmill.

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CHAPTER 1: INTRODUCTION

Long before humans reach adulthood, they are able to walk around daily without consciously thinking about putting one foot in front of the other. Despite its everyday ease, human locomotion is a biomechanically and neuromechanically complex task that requires coordination of multiple limbs and each of their respective degrees of freedom. Due to the unconstrained nature of this everyday function, individuals exhibit unique qualities while walking that make their gait identifiable (Liu et al, 2004; Hawas et al, 2019). These qualities can include step frequency, step symmetry, step length, and limb coordination patterns. When considering all of these variables, it makes sense that the overall complexity of walking can also lead to variability in different individuals' walking patterns.

Variability in gait patterns allows for adaptability. Predictive motor adaptation implies an adjustment to a repeated movement derived from receiving error feedback on a trial basis (Martin et al, 1996). After adaptation occurs, individuals cannot immediately return to the original movement, but instead must go through a period of de-adaptation, also known as washout, to unlearn the learned movement (Bastian, 2010). Movements including throwing, stepping, balancing, and reaching are all adaptable (Martin et al, 1996; Reisman et al, 2005; Horak and Diener, 1994; Shadmehr and Mussa-Ivaldi, 1994) Humans respond to perturbations in their gait or walking environment with astounding success. For example, people can usually avoid falling when they encounter new terrain, such as uneven pavement or ice, by making adjustments that are planned or unplanned. Successful adaptation to these real-world perturbations require active control that can manifest in the form of feedforward (planned) or feedback (unplanned) control mechanisms that alter gait both spatially and temporally (Malone et al 2012). Under normal walking conditions, humans use feedforward control regularly to coordinate planned movements. For example, typical walking requires the contraction of several leg muscles prior to foot contact. If this control did not occur, the leg would collapse on contact (Judge et al, 1996). When the terrain has abnormalities or obstacles, feedforward control requires prior knowledge and awareness of these surface changes to allow for the motor adaptation necessary to negotiate the terrain. In contrast, feedback control is purely reactive and implies no practice or aftereffects (Morton and Bastian, 2006). For example, the usual response to tripping is taking one large step without any planning or conscious thought. This response is exclusively a reaction, not predictive motor adaptation.

Previous studies have demonstrated that each of these processes in locomotor adaptation are derived from different neural structures. In 2006, Morton and Bastian showed that predictive feedforward adaptation is primarily under cerebellar control, and individuals with cerebellar damage were unable to initiate predictive adaptations (Morton and Bastian, 2006). Conversely, reactive feedback control has been shown to be an automatically induced process derived from the spinal cord in humans. It has been demonstrated that human infants are able to initiate reactive adaptation in their gait before the complete development of the corticospinal pathway, which suggests that reactive modifications in gait are controlled at the spinal level (Yang et al, 2005; Yang et al, 2006). In addition, Morton and Bastian showed that adult humans with cerebellar damage were not impaired when making feedback-driven adaptations in gait (Morton and Bastian, 2006). In healthy humans, these two neural processes go hand in hand as the walking environment constantly changes and proprioceptive feedback is constantly needed for spatial awareness in order to adapt to obstacles, changes in terrain, and other locomotor challenges.

Motor adaptation is a learning process that is error-driven and derived from an already well-known movement (Malone and Bastian 2010). A well-practiced skill, such as walking, is a prime candidate for learning about how motor adaptation occurs in different individuals; however, because healthy adults are proficient in walking, it is difficult to create a de novo walking task. Split-belt treadmills are often used to study gait adaptation in healthy individuals, as well as individuals with abnormalities in their gait. Split-belt treadmills allow each foot to be moving at different speeds, and therefore contrive novel walking tasks by introducing a new and predictable demand in the walking environment. These novel walking tasks prompt the participant to learn new walking patterns over a period of a few minutes, or several hundred repetitions. Due to the repetitive nature of the task, this type of motor learning usually induces brief yet observable aftereffects (Morton and Bastian 2005). These aftereffects are washed out much more quickly than the initial learning (Davidson and Wolpert, 2004). The rate and magnitude of adaptation and de-adaptation differs between individuals, as does the method of adaptation (Smith et al, 2006; Yokoyama et al, 2018). Subsequently, adaptation rates and the amplitude of aftereffects can be further applied to learning new environments and new walking tasks (Vasudevan 2017). Previous studies using split-belt treadmills have shown that the initial response to each leg moving at a different velocity is temporal and spatial asymmetry in gait (Malone 2012). Generally, in healthy adults, the gait typically becomes symmetrical gradually over a learning period of a few minutes. Then, when the treadmill returns to baseline conditions, the gait rapidly becomes asymmetric on the opposite side for several stride cycles, before returning to the original symmetrical baseline (Reisman et al. 2007).

The primary purpose of this experiment was to determine the effects of age and familiarity with stepping tasks on locomotor adaptation patterns during a complex walking task. We also tested the effect of gender on the same variables. There are many well-documented differences in gait variables, such as step length, self-selected velocity, and range of motion between young and elderly subjects (Devita and Hortobaygi, 2000). We used a split-belt treadmill to create a novel walking environment for participants and observed the differences in the learning trends they each exhibited by analyzing differences in adaptation strategies and timescales. We measured joint angles, ground reaction forces, and step and stride times using motion capture, force plates, and inertial measurement units (IMU's). We had three hypotheses related to each of these factors based on previous research and inference. First, we hypothesized that overall familiarity with activities demanding balance, particularly walking and running, would contribute most to adaptation for split-belt walking. We expected individuals who regularly performed these activities to adapt faster and maintain aftereffects for longer than others, and consequently exhibit different strategies for maintaining a steady walking pattern. Next, due to previous studies showing age can lead to further dependence on proximal as opposed to distal muscles, we also hypothesized that there would be a move from more distal to proximal adaptation strategies with age (Devita and Hortobagyi, 2000; Savelberg et al, 2007). Additionally, other studies have shown slower adaptation and fewer after effects present in older individuals, so we expected to see a difference in the adaptation timescale (Bruijn et al. 2012). Lastly, there is also some evidence of decreased balance performance in men as they age as opposed to women, though this has largely only been examined in static tasks (Sullivan et al, 2009). We therefore hypothesized that changes in strategy and time scale may change differently in men than in women.

CHAPTER 2: METHODS

2.1 Data Collection

2.1.1 Participants

50 volunteers were recruited for this study. We recruited these participants by word of mouth, with ten participants per decade starting at age 20. There was an equal number of male and female participants. Ultimately, only 26 healthy volunteers participated in this study (9 males and 17 females) due to the COVID-19 pandemic. All participants were between the ages of 20 and 59 years old (**Table 1)**. All participants were free of any neurological or muscular impairments and had normal or corrected-to-normal vision. All participants gave written informed consent before participating. The protocol was approved by the Institutional Review Board at the University of Minnesota. All participants readily completed the study; no participants withdrew.

Table 1: *Recruitment Characteristics.* Ages and genders of participants used in this study (years ± SD). Though grouped by decade here, age was used as a continuous variable for all analyses.

Age Group	Male	Female
20-29	24.75±0.5 (n=4)	27.2±1.3 (n=5)
30-39	32 (n=1)	38±1 (n=3)
40-49	42.5±2.1 (n=2)	44.8±2.9 (n=5)
50-59	55.5±0.7 (n=2)	54.5±2.1 (n=4)

2.1.2 Preparation

The experiment took place in a laboratory equipped with a 12-camera motion capture (OptiTrack, Corvallis, OR) system. We fitted participants with 18 reflective markers using a modified version of the Plug-in-Gait conventional lower body model that included one additional marker on the anterior aspect of each foot as seen in **Figure 1**.

These extra markers were mounted on inertial measurement units (Stryd Inc, Boulder, CO) that were then attached to the participants' shoes, approximately over the base of the 2nd metatarsal. We collected motion capture data at 100 Hz and force data (3D forces and moments and center of pressure) at 1000 Hz on a split-belt force treadmill (Bertec Corporation, Columbus, OH). We collected inertial measurement unit (IMU) data at approximately 412 Hz.

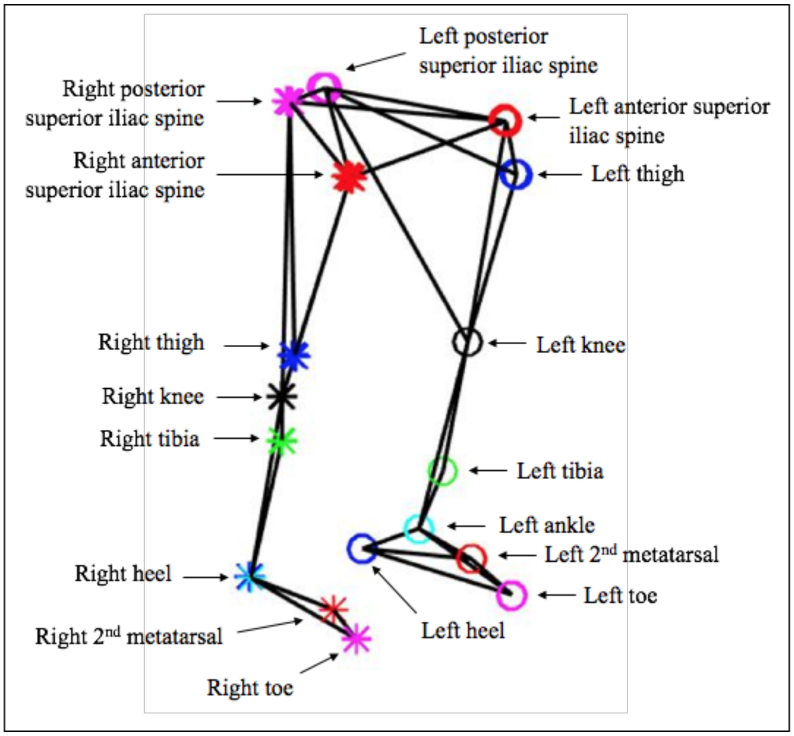

Figure 1: *Marker locations.* Open circles and asterisks indicate markers placed on the left and right sides, respectively. These were mounted according to the Plug-in Gait conventional lower body model. We added additional markers on the 2nd metatarsals.

2.1.3 Experimental protocol

We asked participants to walk on the split-belt force treadmill for a total of 20 minutes. Walking conditions were either considered "tied-belt" or "split-belt." Under tied-belt conditions, left and right belt velocities were synchronized. Under split-belt conditions, each belt moved at a unique velocity. Participants positioned themselves in the center of the treadmill with one foot on each belt. Handrails were available in front of and on either side of the participants while they were walking. If they chose to use the handrails, they were asked to not support their body weight with their arms.

The experiment was comprised of three phases: i) baseline, ii) adaptation, and iii) washout (deadaptation). For the baseline phase, participants walked under tied-belt conditions at a fixed rate of 1.0 m/s for 5 minutes. During the adaptation phase, participants walked for 10 minutes under split-belt conditions at a 1:3 speed ratio. Under these conditions, one belt remained at 1.0 m/s, while the other was slowed to 0.33 m/s. The slow belt was assigned to the dominant foot and the fast belt was assigned to the non-dominant foot. We established foot dominance by asking the participants which foot they would use to kick a ball. For the washout phase, participants walked under tied-belt conditions at 1.0 m/s for 5 minutes.

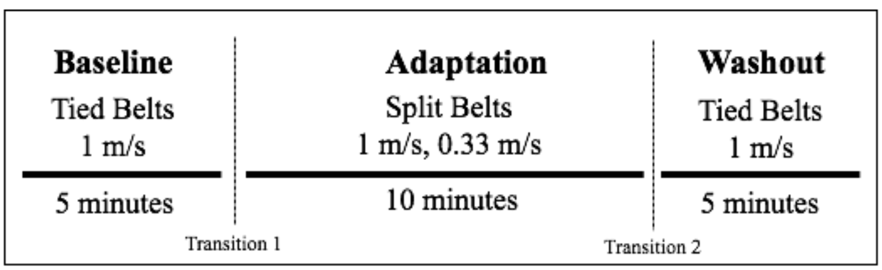

Figure 2: *Experimental paradigm*. Periods of tied-belt and split-belt walking, and the associated conditions.

We gave participants a verbal warning approximately 1 minute before the treadmill started, stopped, or either belt changed velocity. Immediately prior to these transitions, we also gave a countdown three seconds before changing the walking task. We instructed participants to refrain from looking at their feet so as to limit visuomotor feedback. The researcher engaged in casual conversation with each participant to try to limit attention being focused solely on the walking task.

2.1.4 Post-Experimental Steps and Balance Questionnaire

Participants filled out questionnaires (**Appendix D**) to report approximately how many hours they spent performing legged locomotion or balance tasks each week. We corrected reported locomotion tasks to the approximate number of steps, as opposed to hours, as step frequency varies significantly between walking and running by assuming step frequencies of 120 steps/min for walking and 180 steps/min for running. We used these values for later analysis.

2.2 Data Processing and Analysis

To process force and motion capture data, we used a custom-written pipeline in Matlab (MathWorks, Natick, MA) and read in force, motion capture, and IMU data. We synchronized IMU data with the motion capture and force data by using kinematic markers.

2.2.1 Force Data

Before data were processed, force data went through a 70 Hz low-pass fourth order Butterworth filter. We initially identified aerial phases where the derivative of the vertical force data was less than 5, then determined the median of the values for these aerial phases and subtracted for each force and moment to correct for any noise. We determined heelstrikes and toe-offs by identifying where the corrected vertical force data exceeded 100 Newtons and then counting back to where it exceeded 10 Newtons (**Figure 3**).

We did a step by step analysis of the forces to determine step time (heelstrike to subsequent heelstrike on the opposite leg) and impact peak (first peak of force data). The step time for the change side was taken to be heelstrike on that side to heelstrike on the unchanged side (**Figure 3**). Step time for the unchanged side was taken to be heelstrike from the unchanged side to the changed side.

We determined maximum and minimum fore-aft forces for each step and normalized them to percentage bodyweight (**Figure 3**). We calculated the asymmetry index of these data by subtracting the value for the side that did not change speed from the side that did change speed values and dividing that value by the average of these two values.

$$Force\ Asymmetry = \frac{2(Dominant\ Side\ Force - Nondominant\ Side\ Force)}{(Dominant\ Side\ Force\ + Nondominant\ Side\ Force)}$$

Here, a positive value indicates that the side that changed had a larger value and the side that did not change had a smaller value, whereas a negative value means that the side that changed had a smaller value and the side that did not change had a larger value. Sample graphs for baseline, adaptation, and washout fore-aft forces are available in **Appendix D**.

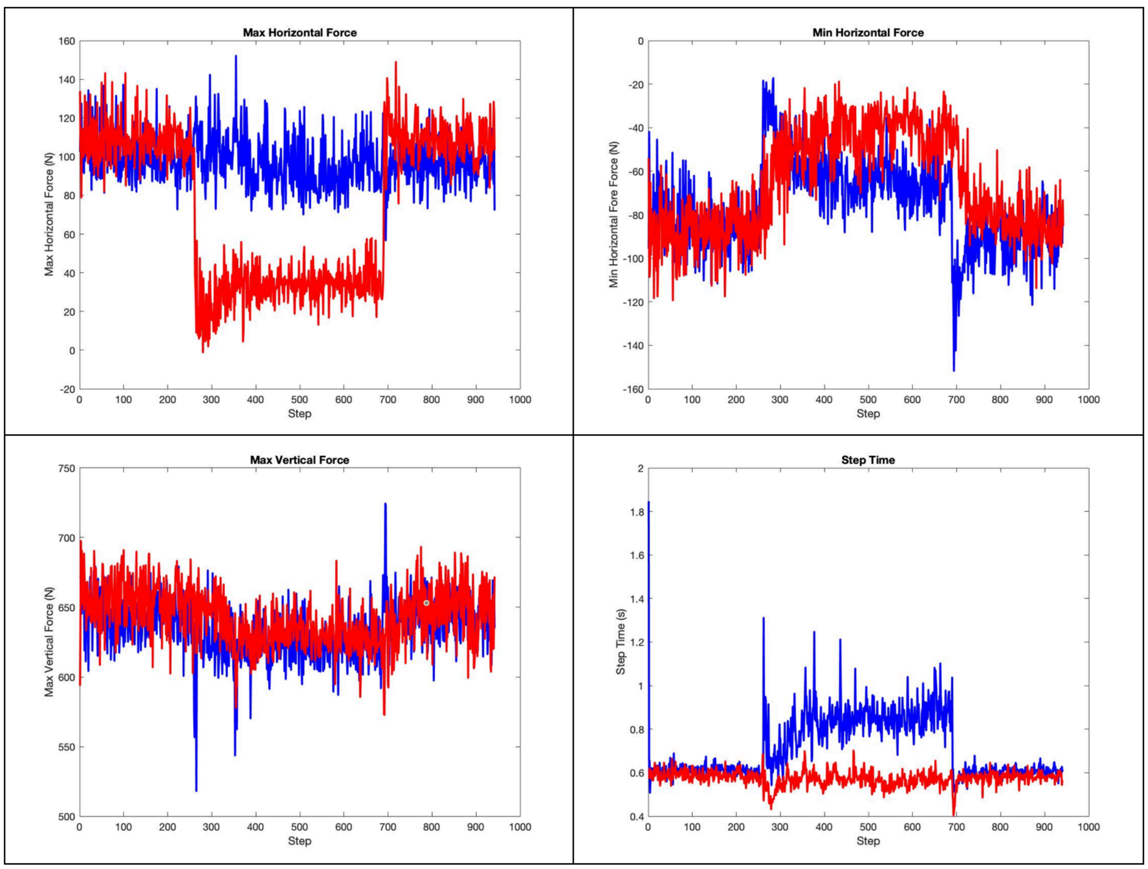

Figure 3: *Sample force graphs*. Graphs here show respective forces for the duration of the experiment where the left foot is indicated by the blue line and right foot is indicated by the red lines.

2.2.2 Motion Capture Data

We used the motion capture data to determine foot, shank, thigh, and pelvis movement. We defined ankle flexion angle to be the angle between the foot and shank, knee flexion between the shank and thigh, and hip flexion between the thigh and pelvis (**Figure 4**). We calculated the asymmetry index of these data by subtracting the value for the side that did not change speed from the side that did change speed and dividing that value by the average of these two left and right values (**Figure 5**).

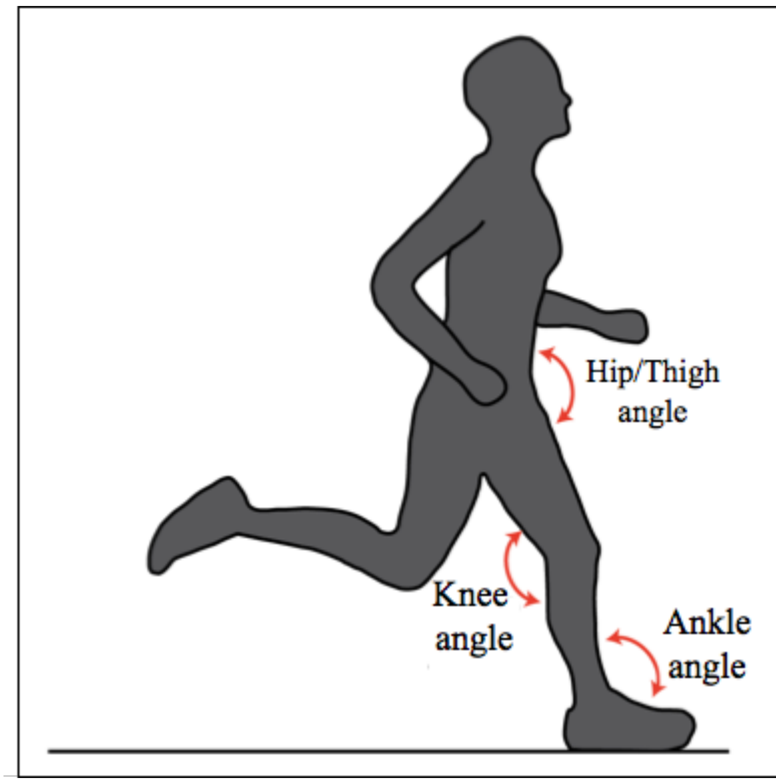

Figure 4: *Joint excursion angles.* Diagram of where joint angles were measured for subsequent analysis. (Adapted from K.L. Snyder)

Magnitude Determination

The magnitude comparison consisted of an examination of how the magnitude of the angular excursion of each joint changed from the time the belts were tied, to the steady-state time following the adaptation period. These time windows were the first 100 steps of the baseline condition (less than if 100 steps were not taken before the first change) and the last 20 steps of the split-belt condition. In all cases, we determined the magnitude changes to be the difference in angular excursion between the conditions by subtracting the baseline value from the value during the untied period for each side and adding these two values together. A negative value therefore represents a decrease in angular excursion and a positive value an increase in angular excursion.

2.2.3 Strategy Determination

We used the asymmetry changes from tied to untied belts to determine the strategy employed by each subject. We examined angular excursion, maximal and minimal fore-aft forces, maximal vertical forces, step times, and other leg metrics across age, number of steps or minutes spent stepping, and gender to determine if the strategy used to adjust to the complex walking task depended upon any of these variables. We used the same time window utilized for the magnitude determination for these calculations. In all cases, we examined the asymmetry difference by subtracting the original asymmetry from that after the belts were untied.

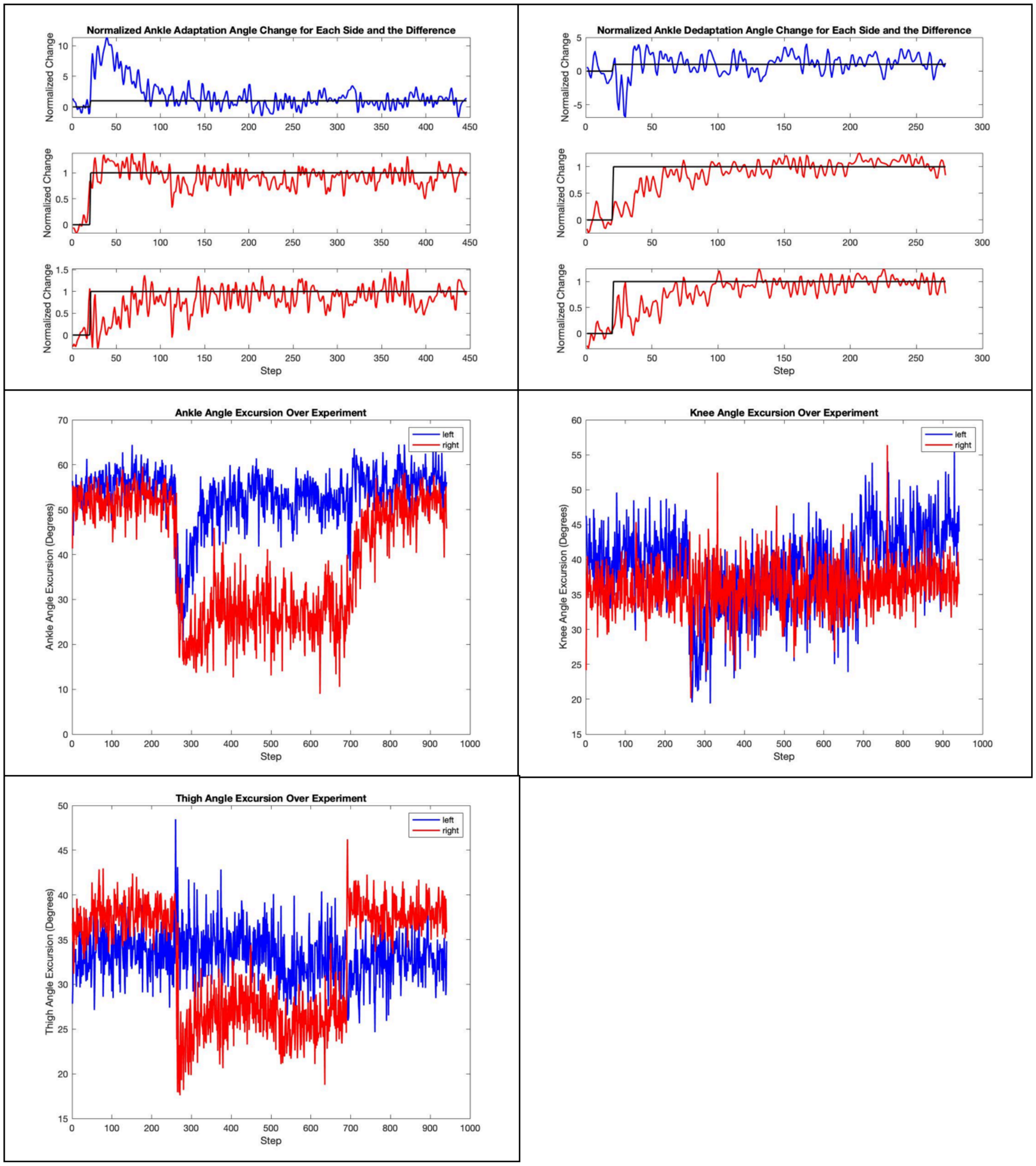

Figure 5: *Sample kinematic graphs*. Graphs here show respective kinematic variables for the duration of the entire experiment where the left foot is indicated by the blue lines and right foot is indicate by the red lines.

2.2.4 Time Scale Determination

We fed the force and motion capture data from above into both single (one pole) and double process (two pole, one zero) models to determine the time scales and amplitudes for learning for each subject using system identification. First, we linearly transformed the data so that all changes had unit magnitude from 0 to 1. We then determined time scale(s) and amplitude(s) for each change, tied to untied belts and untied to tied belts, via the following equations in the complex frequency and time domains:

$Y(s) = [(\frac{1}{\tau_1 s+1})e^{-T_d s}]X(s)$ (1 process)

$Y(s) = [(\frac{A_1}{\tau_1 s+1} + \frac{A_2}{\tau_2 s+1})e^{-T_d s}]X(s)$(2 processes)

And

$\Delta v(t) = [1 - e^{\frac{-(t-T_d)}{\tau_1}}]$ (1 process)

$\Delta v(t) = A_1[1 - e^{\frac{-(t-T_d)}{\tau_1}}] + A_2[1 - e^{\frac{-(t-T_d)}{\tau_2}}]$ (2 processes)

The τ variable can be somewhat unintuitive, so the inverse is often taken and approximately tripled to give the time it takes to go 95% of the total change. Our results present -3/τ for ease of interpretation.

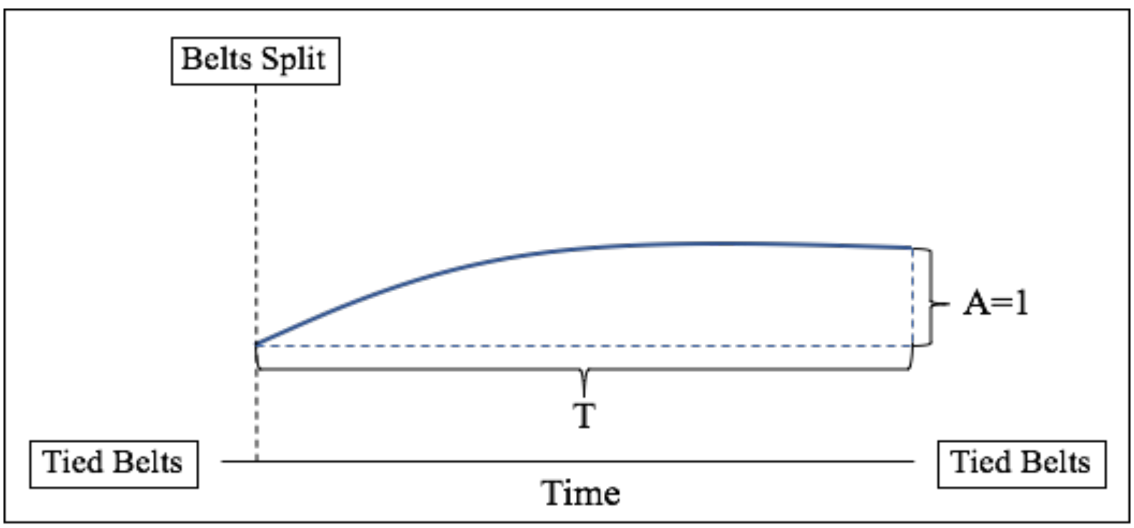

Figure 6: *1-process model example graph*. Adaptation timescale example graph shows under-shooting the steady-state value.

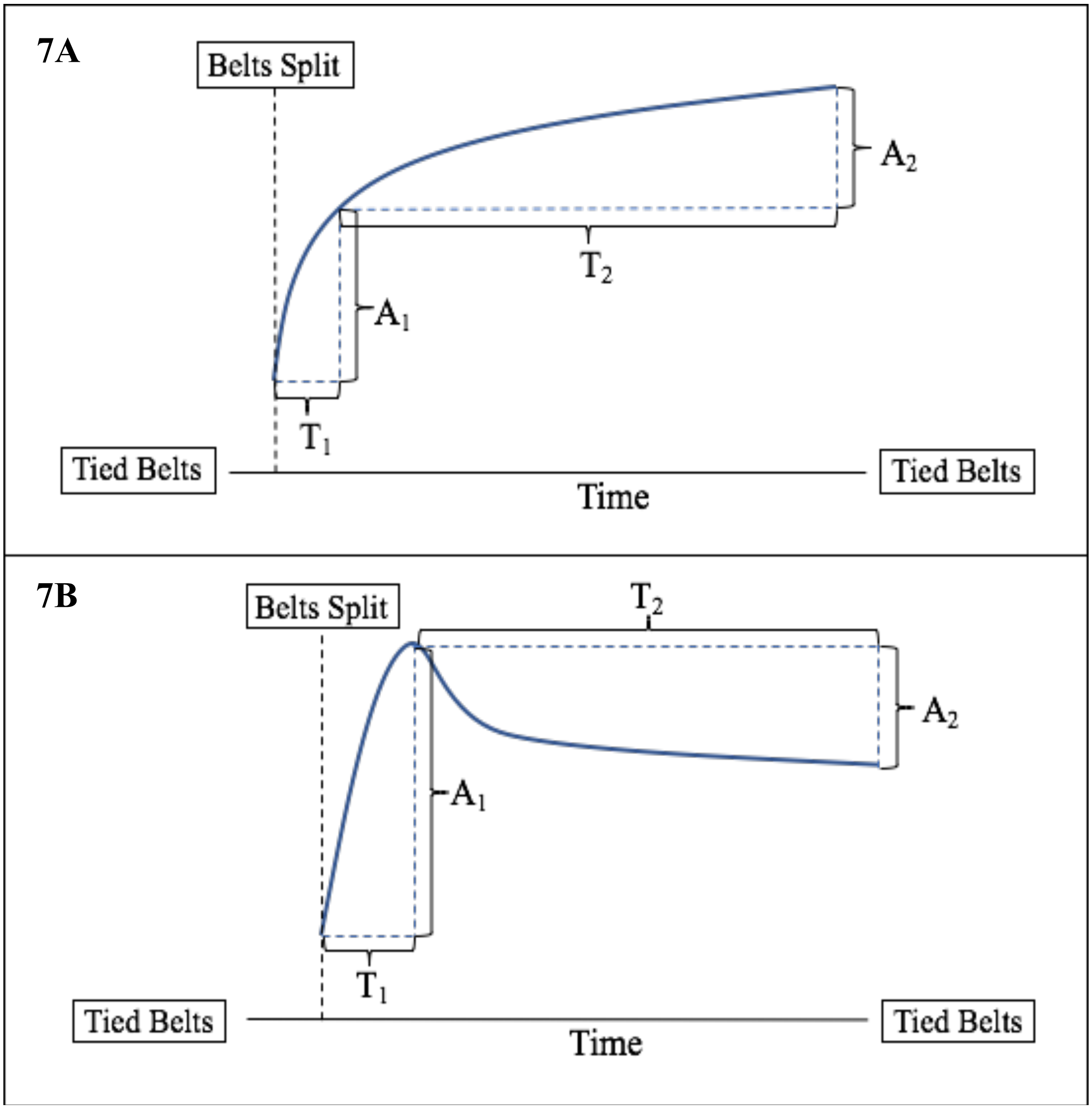

Figure 7: *2-process model example graphs.* Adaptation timescale example graphs where **Figure 7A** shows under-shooting the steady-state value and **Figure 7B** shows over-shooting the steady-state value. T_1 represents the time for the fast adaptation process, where A_1 is the amplitude of change. T_2 represents the time for the slow adaptation process, where A_2 is the amplitude of change.

We measured timescales for both unfiltered data, and data filtered using a 4th order Butterworth filter with an 0.2 Hz lowpass cutoff. The filter allowed for more accurate determination of which model fit was better due to the elimination of step-to-step noise.

For analysis of the timescales, we found values for the difference in timescale between the left and right legs during adaptation and washout. We also found the timescale differences within the dominant leg for adaptation and adaptation. We performed statistical comparisons between genders and across age and stepping experience to determine if any of these variables affected the strategy employed or the time scale on which the subject learned or unlearned the task. We calculated P-values and effect sizes for all comparisons performed, and in the case of p-values of greater than 0.05.

We performed statistical analysis on those angular and force changes that exhibited significant changes ($p<0.05$). In practice, we only included variables that exhibited a model fit that accounted for at least 25% of the change. We calculated correlation values for both amplitudes (in the case of the two-process model) and time constants for variables with sufficiently good model fits.

CHAPTER 3: RESULTS

In all results, the term “steps” will refer to the reported number of steps taken each week. The term “time spent stepping” will refer to the reported time spent walking and running each week. Results are presented as (r, p), where r is the Pearson’s correlation coefficient and p is the p-value. It should be noted that there is an obvious positive correlation between the number of steps and the amount of time spent stepping each week (0.9769, 10^-14). In addition, there was a significant positive correlation between age and minutes spent walking (0.451, 0.0402).

3.1 Spatial

3.1.1 Magnitude

When comparing the magnitudes of ranges of motion across all subjects, we saw no significant correlations with subject age, time spent stepping each week, or number of steps taken each week. When considering only female subjects, this pattern remained consistent as there were no significant interactions. When considering only male subjects, as age increased, thigh angle excursion decreased (-0.813, 0.0261), and as age increased, step time magnitude also decreased (-0.8177, 0.0247). Additionally, we found a significant correlation between the number of steps taken each week and maximum vertical force for male subjects (-0.7625, 0.0462). Correlation graphs for magnitudes can be seen in **Figure 8**. We discovered a number of interactions between dependent variables. These interactions can be seen in **Figure 13** in **Appendix A**.

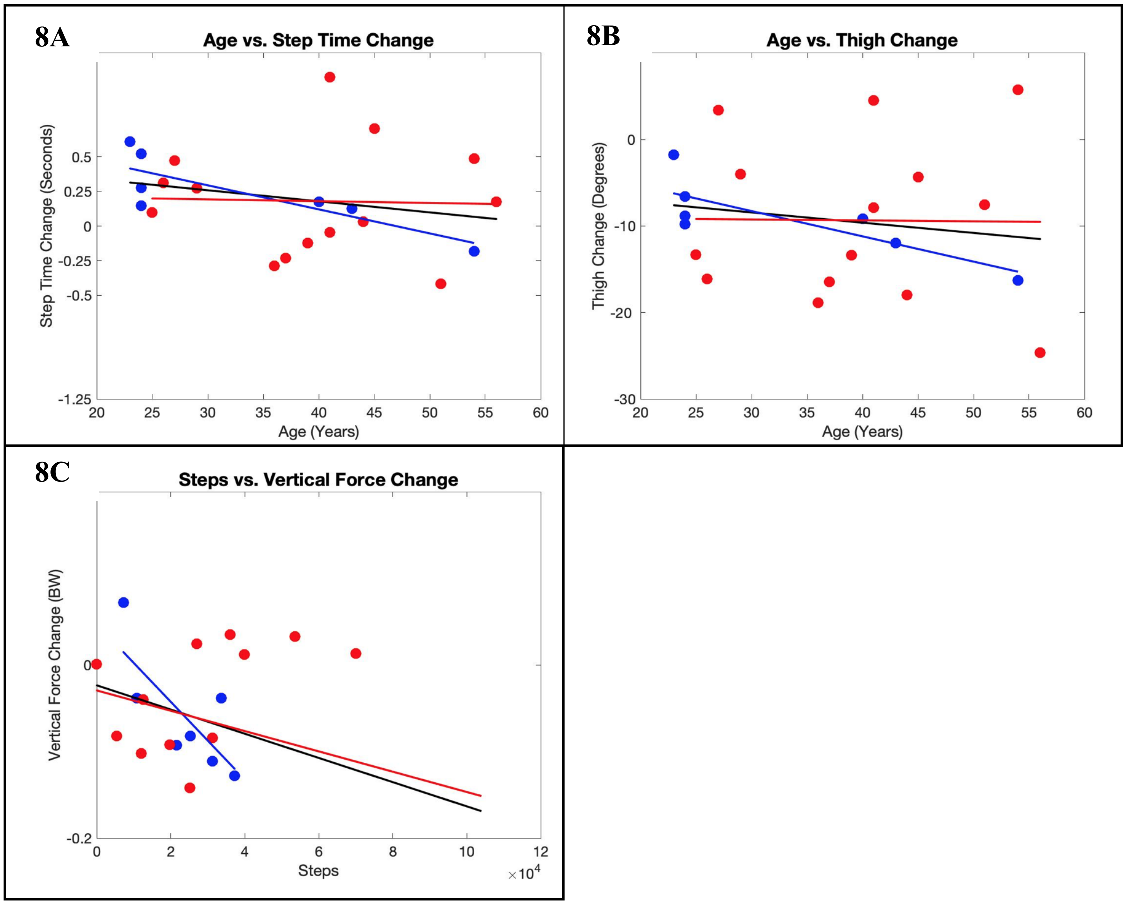

Figure 8: *Adaptation magnitude correlation graphs.* Significant interactions here are only with male participants, shown in blue. **Figure 8A** shows the correlation with age and step time (-0.8177, 0.0247). **Figure 8B** shows correlations between age and thigh angles (-0.813, 0.0261). **Figure 8C** shows correlations between steps taken and vertical forces (-0.7625, 0.0462).

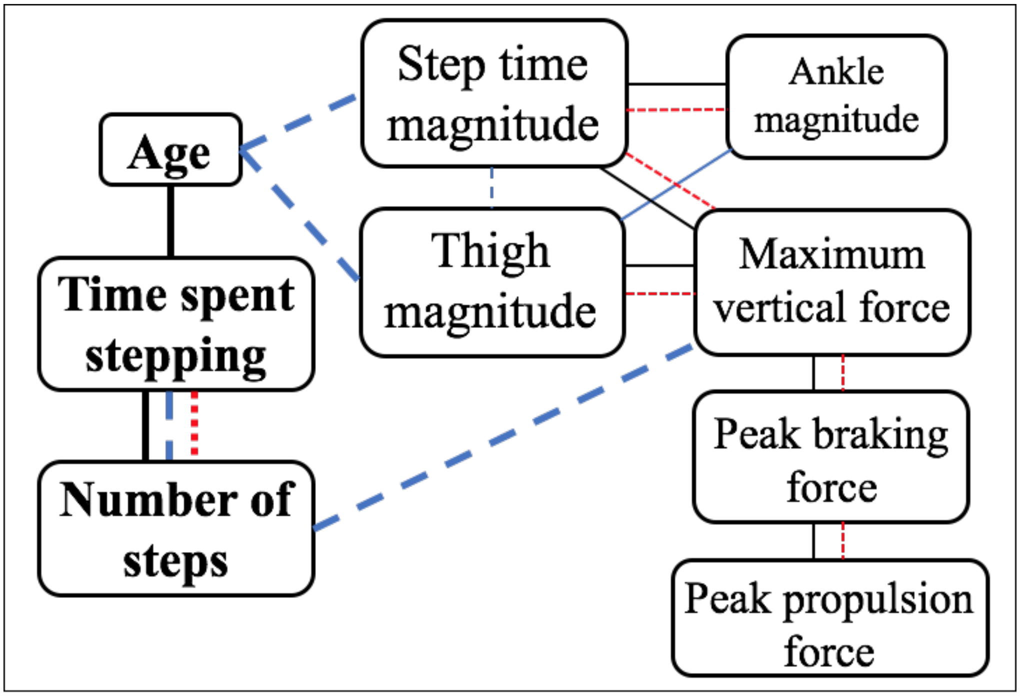

Figure 9: *Magnitude Interaction*s. Network diagram of the significant interactions between variables during the magnitude analysis. Independent variables are shown in bold on the left side of the figure. Thick lines indicate interactions with independent variables while thin lines indicate interactions between dependent variables. Solid lines are analyses including all subjects, dashed blue lines are analyses with only male subjects, and dotted red lines are analyses with only female subjects.

3.1.2 Adaptation Strategy

When comparing the joint asymmetry patterns, there was a moderate correlation between age and peak braking force (-0.5353, 0.0125). There were no significant correlations observed between joint asymmetry and time spent stepping or number of steps taken each week. When considering only female subjects, we found age was more strongly correlated with the peak braking force (-0.5904, 0.0262). When considering only male subjects, there was a significant correlation between age and step time asymmetry (-0.7548, 0.0499). Correlation graphs for adaptation strategy can be seen in **Figure 10**. Significant interactions between dependent variables can be seen in **Figure 14** in **Appendix A**.

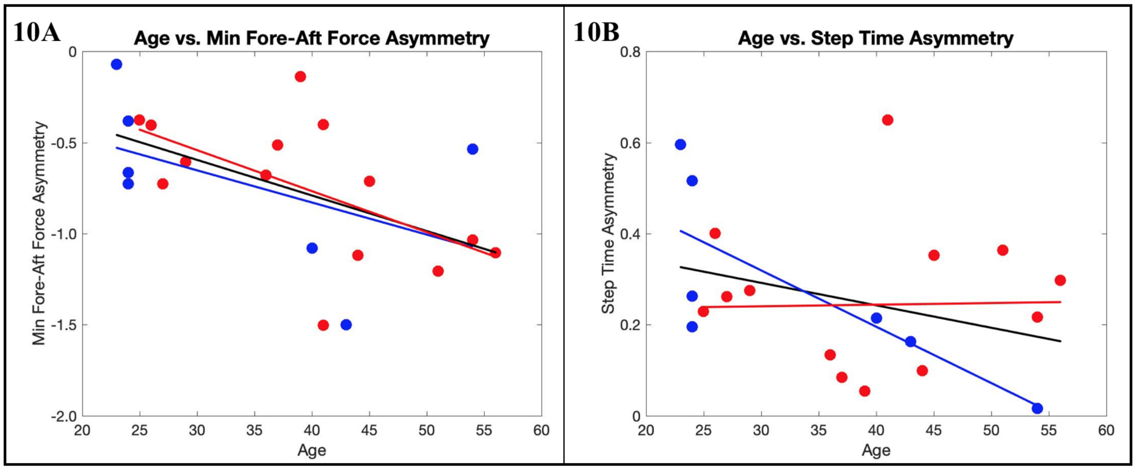

Figure 10: *Adaptation strategy graphs.* Significant interactions in **Figure 10A** are with all subjects (-0.5353, p=0.0125), indicated by the solid black line, and females only (-0.5904, p=0.0262), indicated by the red line. Significant interactions in **Figure 10B** are with male subjects only (-0.7548, p=0.0499), indicated by the blue line.

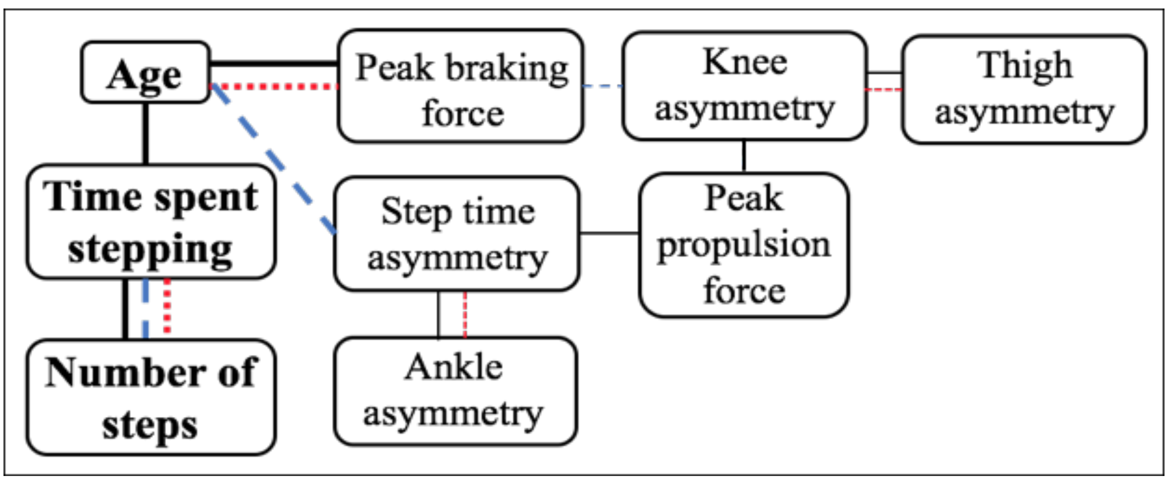

Figure 11: *Strategy Interactions*. Network diagram of the significant interactions between variables during strategy analysis. Independent variables are shown in bold on the left side of the figure. Thick lines indicate interactions with independent variables while thin lines indicate interactions between dependent variables. Solid lines are analyses including all subjects, dashed blue lines are analyses with only male subjects, and dotted red lines are analyses with only female subjects.

3.2 Temporal

Steps taken each week and time spent stepping each week were tightly correlated.

Therefore, to reduce redundancy, only results for steps taken each week are reported.

Results will be described as "between legs" and "dominant leg." "Between legs" refers to the asymmetry between each leg, and "dominant leg" refers to differences seen within the slowed leg only. Here, we only present data for the 1-process model due to the inconsistency of fit when using the 2-process model. Results for the 2-process model are shown in **Table 3 - 5** in **Appendix E**.

3.2.1 1-process timescale model for ages

There was a negative correlation between the age of the participant and the adaptation timescale for the knee angle difference between legs (-0.7953, 0.0325). There was also a negative correlation between the age of the participant and the washout timescale for the thigh angle within the dominant leg (-0.5051, 0.0231). When considering only female subjects, there was a positive correlation between the washout timescale for step time within the dominant leg (0.7679, 0.0261). When considering only male subjects, there was a prominent negative correlation with the washout timescale for the difference in knee angle between legs (-0.9998, 0.0121). Similarly, for males, there was a prominent negative correlation with the washout timescale for the knee angle within the dominant leg (-0.9988, 0.0001). Correlation graphs are presented in **Figure 12**.

3.2.2 1-process timescale model for steps taken

There was a positive correlation between steps taken and the adaptation timescale for the difference in vertical force between legs (0.7156, 0.0089). There was a positive correlation between steps taken and the adaptation timescale for propulsive force within the dominant leg (0.7144, 0.0001). When considering only female subjects, this pattern was enhanced (0.7322, 0.0019). Lastly, when considering only male subjects, there was a positive correlation between steps taken and the washout timescale between legs for vertical force (0.8794, 0.0494). Correlation graphs are presented in **Figure 13.**

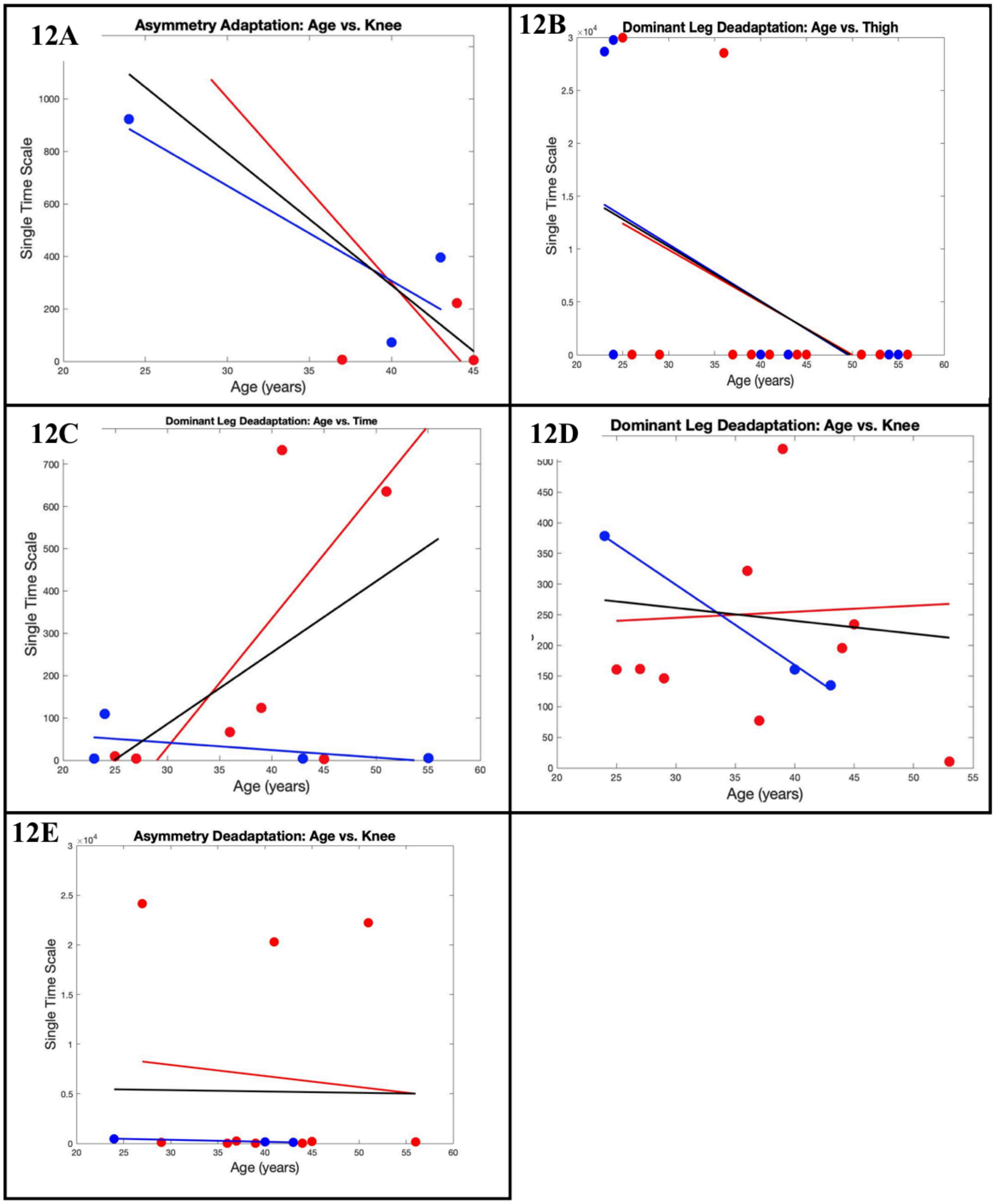

Figure 12: *1-Process timescale graphs for difference across ages*. **Figure 12A** shows the correlation with knee angles between legs during adaptation (-0.7953, 0.0325) and **Figure 12B** shows the correlation with thigh angles during washout in the dominant leg (-0.5051, 0.0231) for analyses with all subjects, indicated by a black line. **Figure 12C** shows the correlation with step time during dominant leg washout (0.7679, 0.0261) and is only significant for female subjects, indicated by a red line. **Figure 12D** shows the correlation with knee angle washout in the dominant leg (-0.9998, 0.0121) and **Figure 12E** shows the correlation for knee angle between legs during washout (-0.9988, 0.0001).

Figure 12D and **Figure 12E** show significant correlation for male subjects only, indicated by a blue line.

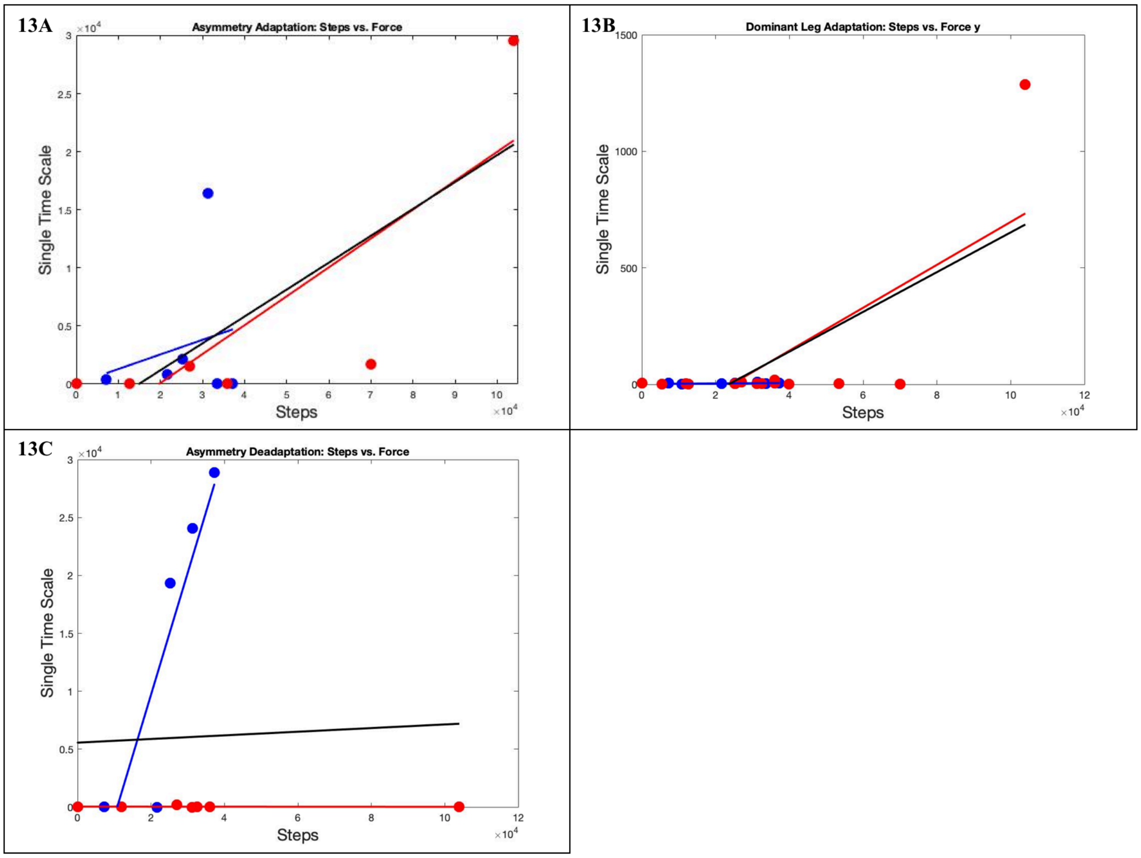

Figure 13: *1-Process timescale graphs across steps*. **Figure 13A** (0.7156, 0.0089) shows significant correlations between steps taken and vertical forces during adaptation between legs in all subjects. **Figure 13B** shows significant correlations between steps taken and propulsive force in the dominant leg during adaptation. This interaction was significant for analysis of all subjects (0.7144, 0.0001), and females only (0.7322, 0.0019). **Figure 13C** (0.8794, 0.0494) shows the correlation between steps taken and vertical forces between legs during washout for all subjects. Analyses with all subjects are shown in black and analyses with females only are shown in red.

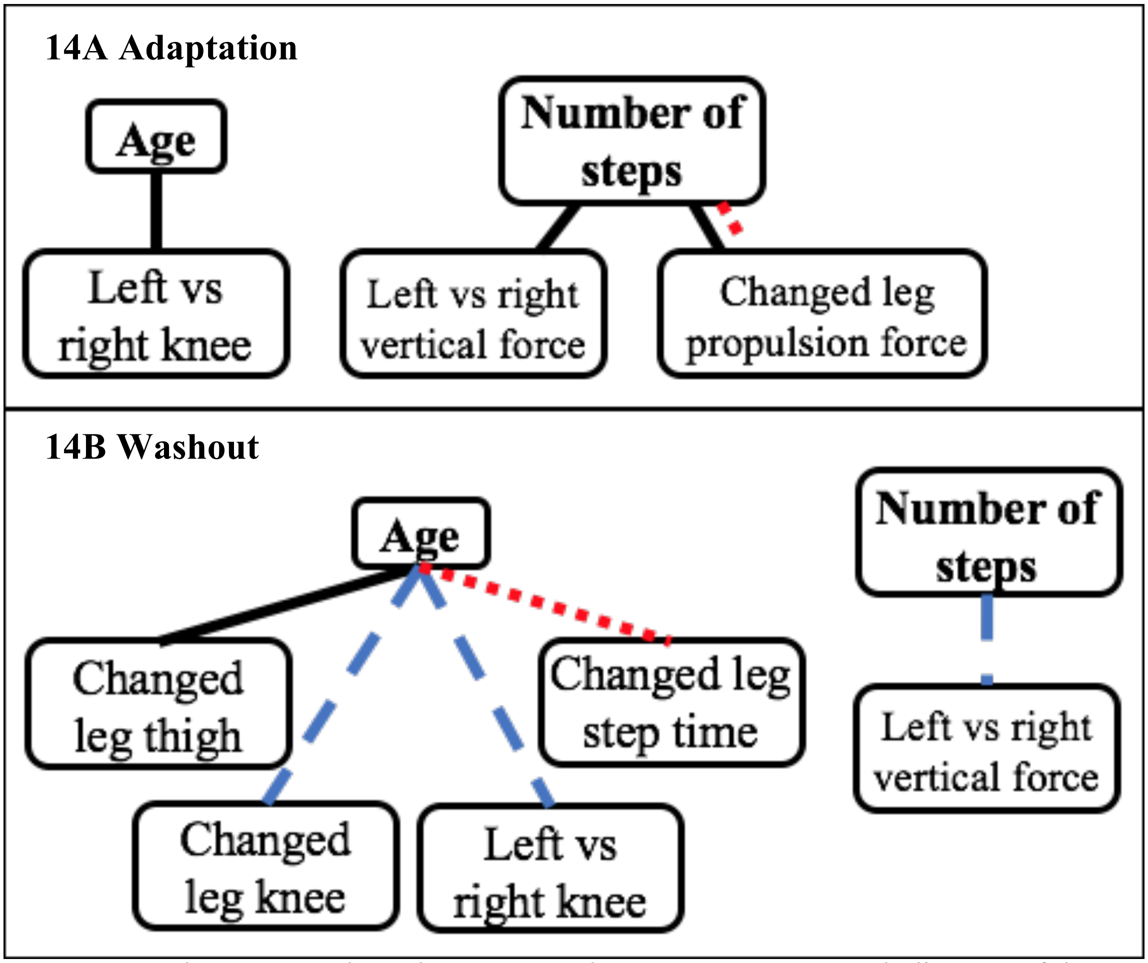

Figure 14: *Adaptation and Washout Timescale Interactions*. Network diagram of the significant interactions between variables where **Figure 14A** is adaptation timescale analysis and **Figure 14B** is washout timescale analysis. Independent variables are shown in bold on the left side of the figure. Thick lines indicate interactions with independent variables while thin lines indicate interactions between dependent variables. Solid lines are analyses including all subjects, dashed blue lines are analyses with only male subjects, and dotted red lines are analyses with only female subjects.

3.3 Summary of Spatial and Temporal Results

Table 2: *Summary of significant interactions between independent variables and dependent variables.* Timescale results are expressed as either "between legs," indicating there were differences between the left leg and right leg, or "dominant leg," indicating there were differences within the slowed leg. All values had $p<0.05$.

Table 2.1: *All participants*

Analysis	Independent variable	Dependent variable
Strategy	Age	Braking force
Timescale	Age	Knee adaptation, between legs
Timescale	Age	Thigh washout, between legs
Timescale	Steps	Vertical force adaptation, between legs
Timescale	Steps	Propulsion force adaptation, dominant leg

Table 2.2: *Female participants only*

Analysis	Independent variable	Dependent variable
Strategy	Age	Braking force
Timescale	Age	Step time washout, dominant leg
Timescale	Steps	Propulsion force adaptation, dominant legs

Table 2.3: *Male participants only*

Analysis	Independent Variable	Dependent variable
Strategy	Age	Step time
Magnitude	Age	Thigh angle
Magnitude	Age	Step time
Magnitude	Steps	Vertical force
Timescale	Age	Knee washout, between legs
Timescale	Age	Knee washout, dominant leg
Timescale	Steps	Vertical force washout, dominant leg

CHAPTER 4: DISCUSSION

Our results indicate that age, gender, experience with stepping, and time spent stepping can all play an important role in locomotor adaptation when the walking environment is altered. Previous studies tend to group participants based on these factors, but we chose to examine each individual and their unique gait adaptation characteristics to discern if there was a dominating factor. For secondary analyses, we did separate tests focusing on each gender to determine how gender influenced those same gait adaptation parameters. Overall, our results reinforce the notion that many factors play interactive roles in gait adaptation.

The number of steps taken each week could predicts the time it takes to reach an adapted steady-state for vertical and horizontal forces.

We postulated that experience with stepping tasks, such as walking and running, would play a significant role in how individuals adapt to a complex walking task. It seems logical that individuals who spend a lot of time walking or running in variable environments would adapt readily to the environmental perturbation we contrived. While we saw little evidence in the similarities with how people adapt or how much they adapt, we did find noteworthy differences in the rate in which they adapt with respect to their reported steps. Specifically, we found differences with adaptation timescales for vertical and horizontal forces that corresponded with the number of steps reported. Contrary to what we expected, we found it took longer for people who walk and run often to reach an adapted steady-state for vertical forces between legs (0.7156, 0.0089) and propulsive forces in the dominant leg (0.7144, 0.0001). It should be noted these results are dominated by outliers. Interestingly, in all of our analyses, including males alone and females alone, the only significant interactions for adaptation rates as they corresponded with steps reported were with force values.

We speculate that there could be different reasons for this observation. First, due to the fact that we saw no correlations with kinematic variables with respect to steps taken, we think there could be multiple interlimb coordination patterns employed that could achieve similar force values. If this was the case, we would expect joint angle patterns to be washed out by the variation, while the force correlations remained significant. **Figure 9** and **Figure 11** both show the intricacies of the interactions we observed between dependent variables. The correlations between forces or step time and joint angles illustrate that the behavior at multiple joints contribute to these values, but they are not defined by a single angle. Similarly, more experienced participants could have more muscularly efficient ways or multiple ways to produce the same forces, which would lead to correlations in kinetic variables, but not kinematic variables.

We speculate that an alternative reason for these results could be that people who take more steps each week go through an exploratory process for gait adaptation. Previous studies on motor learning have suggested that there may be an exploratory phase to learning a new movement where the stakes are perceived to be low, so variability of the motion is high (Wu et al, 2016). Here, if our subjects were well-versed in complicated stepping activities, such as trail running or hiking, it could be speculated that the repetitive nature of the split-belt task was actually perceived to be simple, so they took longer to reach steady-state as they were exploring different motor patterns to minimize metabolic cost or maximize efficiency. To contrast, Wu et al demonstrated that when the stakes were high, such as when a reward was offered, precision was also high and movements were less variable (Wu et al, 2016).

Age did not play a distinct role in adaptation criteria.

We hypothesized that we would find evidence of age-related changes in gait variables when faced with perturbations in the walking environment. We specifically expected to see a shift from distal adaptation techniques to more proximal techniques, as previous studies have shown drastic decreases in ankle usage with obvious compensation at the hip (Hortobagyi et al, 2016). There are well-documented changes in the human gait associated with age. Specifically, the literature reports decreases in walking speed and stride length in older adults (Hortobagyi et al, 2000; Judge et al, 1996). These changes are usually compensated for with an increase in cadence to maintain an overall unchanged walking speed when compared to their younger counterparts (Hortobagyi et al, 2000; Judge et al, 1996). These changes have been attributed to a wide variety of factors, including joint kinematics and power generation (Hortobagyi et al, 2000). It is not clear, however, exactly how physical activity contributes to differences in gait adaptation variables. Previous research has shown that age-related gait shifts can be mitigated by physical activity and other healthy lifestyle qualities (Boyer et al, 2012; Koster et al, 2012; Graf et al, 2005). However, the precise interactions, especially when considering adaptation to variations in the walking environment as opposed to overground walking at a self-selected pace, remain unclear.

Per the literature, we expected to see an increase in angular excursion at the hip in our older participants (Hortobagyi et al, 2016). Our results were in agreement with this notion, but only for male subjects. Male participants showed a reduction in thigh range of motion that increased with age. Additionally, we found differences in how our participants adapted as well as the rate in which they adapted with respect to age. Specifically, we found that, as our subjects aged, their braking forces were more asymmetrical. This result may indicate that, as people age, they may use power absorption, as opposed to power production, to account for acceleration or deceleration needs demanded by the environment. Power production is metabolically costly, which may be a more critical factor in older people. If this were the case, we would expect to see a greater braking peak asymmetry strategy implemented.

In terms of adaptation and washout rates with respect to age, we saw older participants reach steady-state faster than younger participants for knee adaptation and thigh washout. We speculate that joint angle symmetry could be more essential for feelings of overall stability initially. For this reason, it is possible that our older participants immediately compensated at the knee or hip, which are two highly biomechanically related structures, to gain a feeling of stability right away. Then, they may have altered their braking and propulsive forces at a slower rate to further optimize their walking pattern, which would have led to variability in these values for a longer period of time. It has been demonstrated that when precision is needed, such as when incentivized with a reward, or in our case, avoiding a fall, motor variability is decreased (Wu et al, 2016). However, when there is no reward or risk of fall, variability and motor learning are coupled for optimization (Wu et al, 2016). Based on this logic, it makes sense that these simple joint parameters adapted more quickly than the more complex ones.

There are gender differences in adaptation and washout with respect to age and stepping activities.

We saw stark differences in the qualitative and quantitative aspects of our experiment when comparing males and females. Overall, we saw more significant correlations within the group of male participants, and there was no overlap between the significant correlations found with males and females. However, for some of these correlations, there was much smaller statistical power for our limited male subject pool, which may have led to trends that did not rise to the level of statistical significance. Additionally, there were several interactions that were unique to males, but due to a small pool of males, it is likely that some were significant only due to being overdetermined.

There are several possible reasons for the differences we observed. First, we had a much smaller group of male subjects than female subjects. Therefore, the results we found for this group may be more linked to the individuals we were able to recruit, whereas the female subjects may be more representative of their overall gender. Secondly, the subjects who had the most experience with stepping tasks, including one who spent hours on trail a week, were female subjects. This trend could lead to a combined experience and gender effect for females that is not easily separated. Third, and most likely, there are structural differences in lower-body female anatomy, both in terms of shorter height/leg length and hip width/q-angle that could lead to a tendency toward strategies that may be more optimal for female anatomy or male anatomy.

We found differences in strategy where males showed significant correlations between age and step time asymmetry, and females showed significant correlations between age and braking peak. These differences could be related to anatomical distinctions in the lower body. Specifically, females generally have shorter legs due to their overall shorter heights, which limits the step length/step time combinations that they can produce when walking velocity is fixed. Essentially, they may not be able to have long enough step times in order to compensate for the difference in treadmill belt speeds, at any age. Instead, females may need to mitigate how large their braking forces are on either side to produce the negative impulses necessary to be at steady-state on a treadmill with untied belts. In this case, they can't make their steps longer, so they have to make their braking peaks larger in magnitude in order to produce the necessary impulse. On the other hand, males could be able to produce more consistent forces for varying periods of time to change impulse. It is possible that males do some of this mitigation with modulating the braking force as well, as their correlation value, while not statistically significant, also showed an upward trend with age; however, our results indicate they can do most of the modification with step length and step time. It is also possible that, if there were a smaller speed difference between the treadmill belts that was within the range of step time modulation for women, we may have seen a different pattern between step time asymmetry and age in women as well.

Inertial measurement units are a viable source of information on step times.

In addition to our primary analyses, we also aimed to test the integrity of shoe-mounted inertial measurement units (IMU) in gait studies. We found that all step-time data derived from the IMUs was sufficiently similar to the same data derived from the treadmill force plates. Further, step time magnitude changes also showed significant correlations with ankle and thigh angle and vertical force magnitude changes, and step time asymmetry showed significant correlations with ankle angle and knee angle asymmetry. These results imply that future studies could use more inexpensive equipment to gain the same understanding, which could open avenues for research in settings where funding or space is limited. The inexpensiveness and ease of use of IMU's could also allow for studies/data-tracking in more real-world situations in addition to those contrived in a lab.

Limitations.

Our study was limited by a number of factors. First, skin-mounted motion capture markers are inherently limited due to movement on the surface of the skin and the surface of clothing. Additionally, we had a unique subject pool that would not be considered representative of the general population, as our older participants tended to be more physically active than the younger participants. We did mathematically correct for the relationship between steps and age, but this correction only strengthened the relationship between these two variables. This correction further indicates that there is a mitigating effect of steps on age-related gait changes, which is in agreement with previous studies on age-related gait changes (Boyer et al 2012). We tested almost twice as many female participants as male participants, so statistical power is weaker for the group of males. Lastly, we relied heavily on physical activity data that was self-reported. To address these limitations, future studies could use a more longitudinal approach where activities were more closely monitored with a larger, more dispersed subject pool.

Conclusions.

Overall, we found changes due to experience, age, and gender in magnitude, strategy, and timescale of adaptation in a complex walking task. These changes showed the complex, interactive relationships with these variables in terms of adaptation to a complex walking task in practice. Anatomical differences in males and females may lead to different strategies of adaptation across age. Our results indicated the IMUs may be useful for inexpensively tracking certain gait variables in more real-world situations. While our study did have some limitations, it adds to the body of knowledge about the roles of these variables in gait adaptation. More focused, longitudinal studies would be beneficial in teasing out the complex interactions between the variables we measured here to determine the most prominent factors in gait adaptation.

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APPENDIX

Appendix A: Graphs of all significant interactions between dependent variables

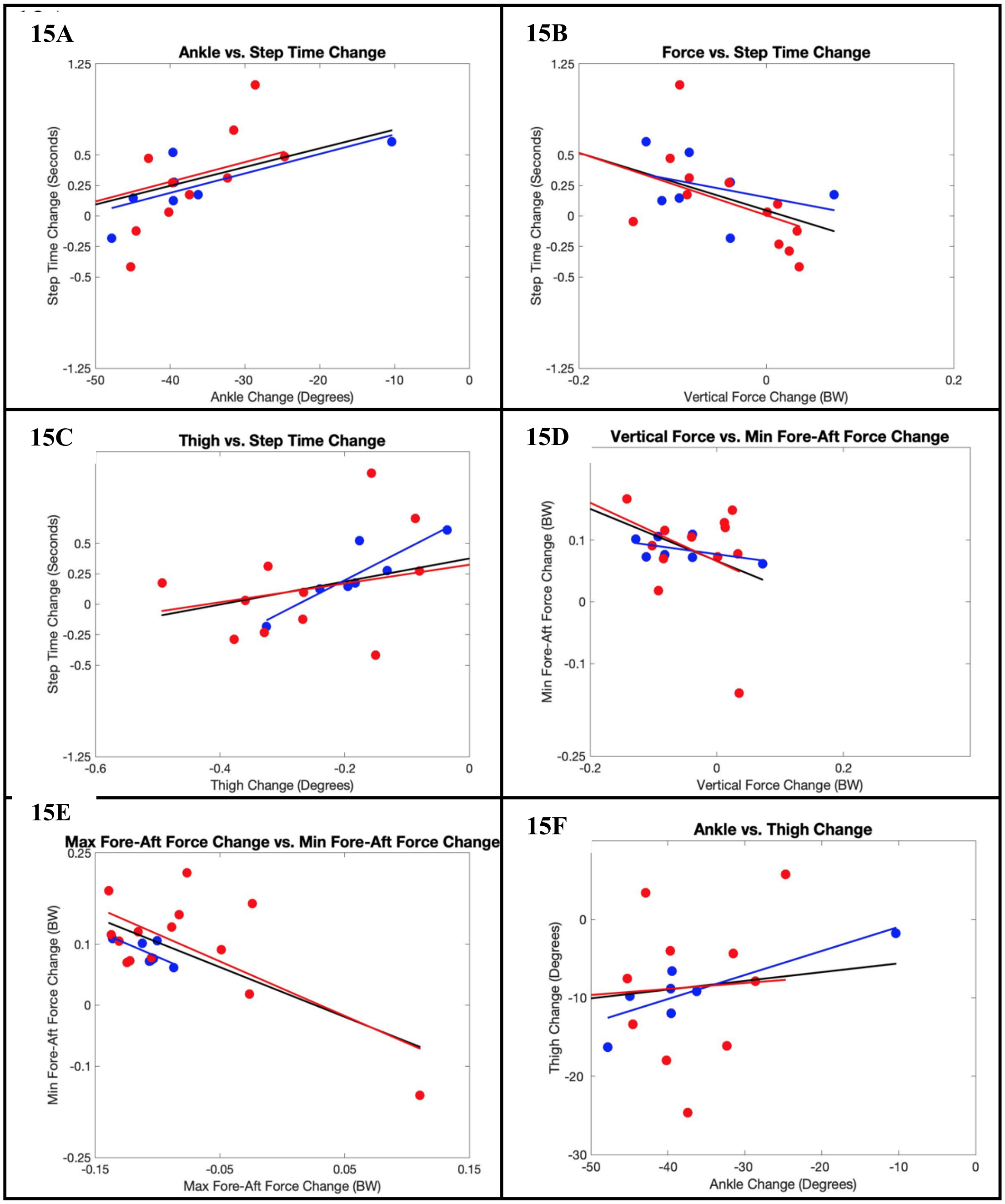

Figure 15: *Adaptation magnitude graphs for dependent variables*. Analyses with all subjects are indicated with a black line, analyses with females only are indicated with a red line, and analyses with only male subjects are indicated with a blue line. **Figure 15A** shows significant interactions for all subjects (0.6857, 0.0006), and significant interactions for females only (0.6836, 0.0007). **Figure 15B** shows significant interactions for all subjects (-0.5914, 0.0047), and females only (-0.6415, 0.0134). **Figure 15C** shows significant interactions for males only (0.8856, 0.008). **Figure 15D** shows significant

interactions for all subjects (-0.5337, 0.0127) and females only (-0.5564, 0.0388). **Figure 15E** shows significant interaction for all subjects (-0.6389, 0.0018) and females only (-0.6813, 0.0073). **Figure 15F** shows significant interactions for males only (0.8425, 0.0174).

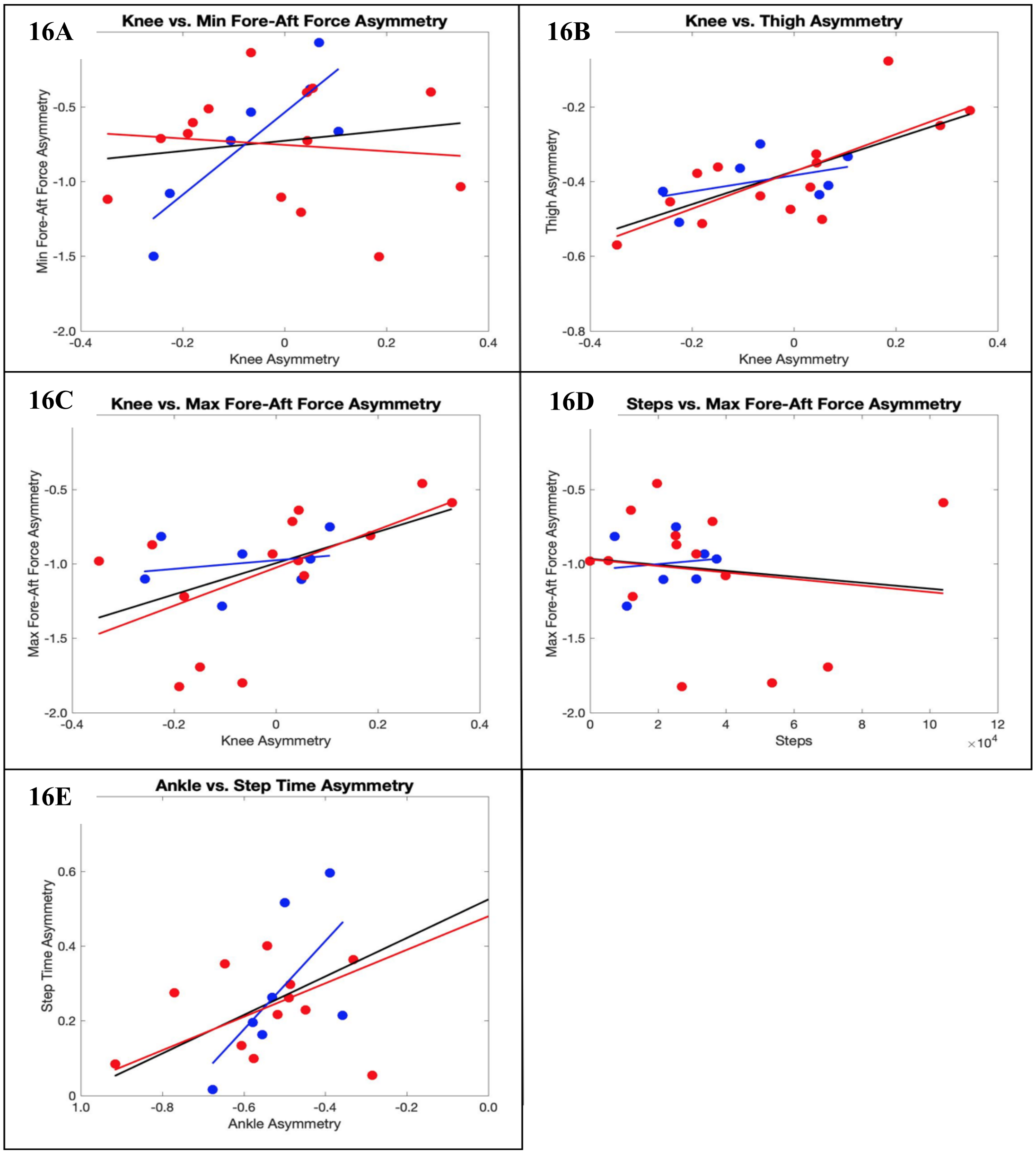

Figure 16: *Adaptation strategy graphs for dependent variables.* Analyses with all subjects are indicated with a black line, analyses with females only are indicated with a red line, and analyses with only male subjects are indicated with a blue line. **Figure 16A** shows the correlation between knee angle and braking force (0.5102, 0.0181) for male subjects only. **Figure 16B** shows the correlation between knee angle and thigh angle (0.6993, 0.0004), and **Figure 16C** shows the correlation between knee angle and propulsive force (0.5102, 0.0181) for all subjects. **Figure 16D** shows the correlation between step time asymmetry and propulsive forces (0.4827, 0.0267) for all subjects.

Figure 16E shows the correlation for ankle angle and step time asymmetry (0.6349, 0.0147) for female subjects only.

Appendix B: Results that do not rise to the level of statistical significance ($0.05<p<0.1$)

Magnitudes
For analyses with all subjects, we found a negative trend in minutes spent stepping and vertical force (-0.6805, 0.0925), as seen in **Figure 17A**.

For dependent variables, we found negative trends between ankle angle and vertical forces (-0.4082, 0.0662), and knee angles and thigh angles (-0.3837, 0.0859). These trends are shown in **Figure 17B** and **Figure 17C**, respectively. There was also a moderate positive trend between thigh angle and step time asymmetry (0.4172, 0.0599), which is shown in **Figure 17C**.

We found a moderate positive trend between age and minutes spent stepping for female subjects (0.4799, 0.0824). For dependent variables, we found a moderate negative trend with ankle angle and vertical forces (-0.4651, 0.0937) in female participants. This trend is shown in **Figure 17B**.

There was a negative trend between minutes spent stepping with vertical force (-0.6805, 0.0925), and minutes spent stepping with propulsive force (-0.7537, 0.0504) for male subjects. These are shown as a solid blue line in **Figure 17A** and **Figure 18A**, respectively. There was a positive trend between minutes spent walking and braking force (0.7293, 0.0629) for male subjects, as seen in **Figure 18B**. There was a negative trend between steps taken and propulsive force (-0.677, 0.0948) for male subjects, seen in **Figure 18C**.

For dependent variables, we found a negative trend between propulsive and braking forces (-0.6789, 0.0935) for male subjects, seen in **Figure 18D**.

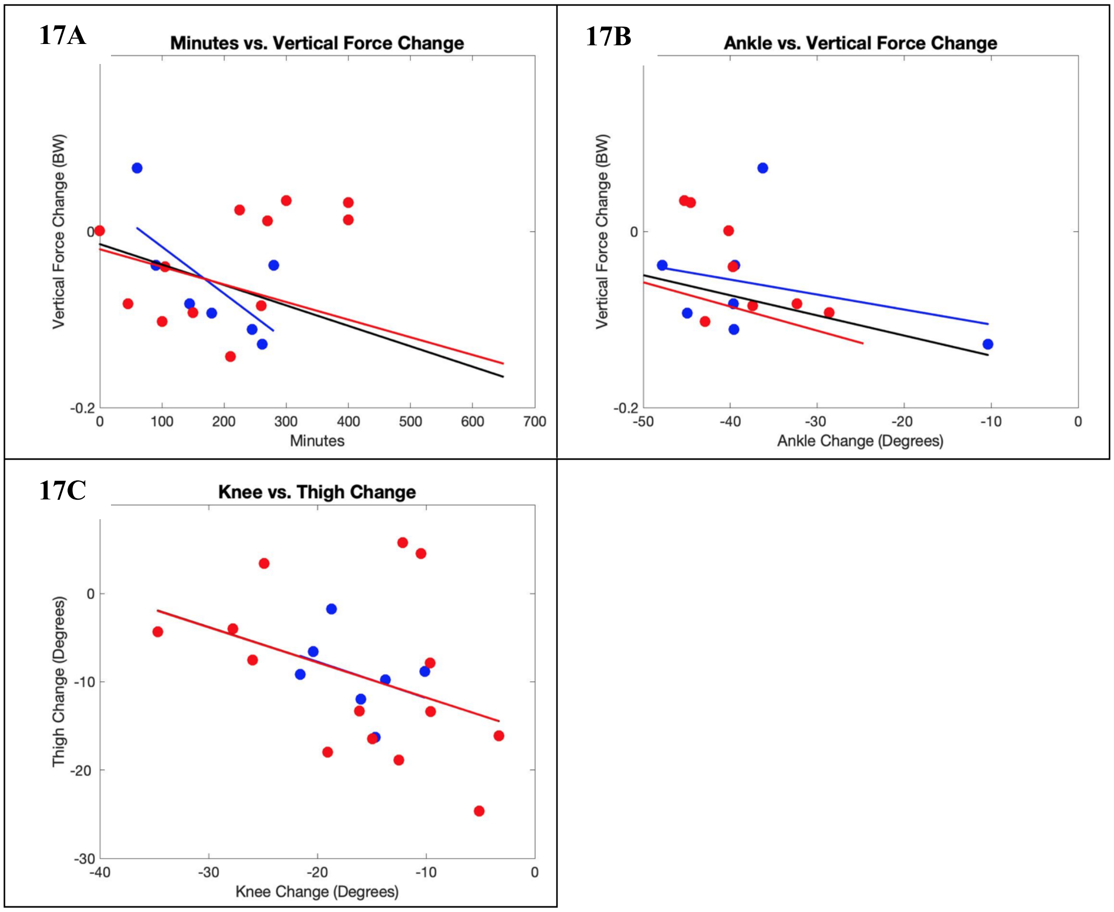

Figure 17: *Trends in magnitude for all subjects.* Analyses with all subjects are indicated with a black line. **Figure 17A** shows a negative trend with minutes and vertical force. **Figure 17B** and **Figure 17C** show trends between dependent variables. **Figure 17B** shows noteworthy trends for analysis of females only, as well, which is shown in red.

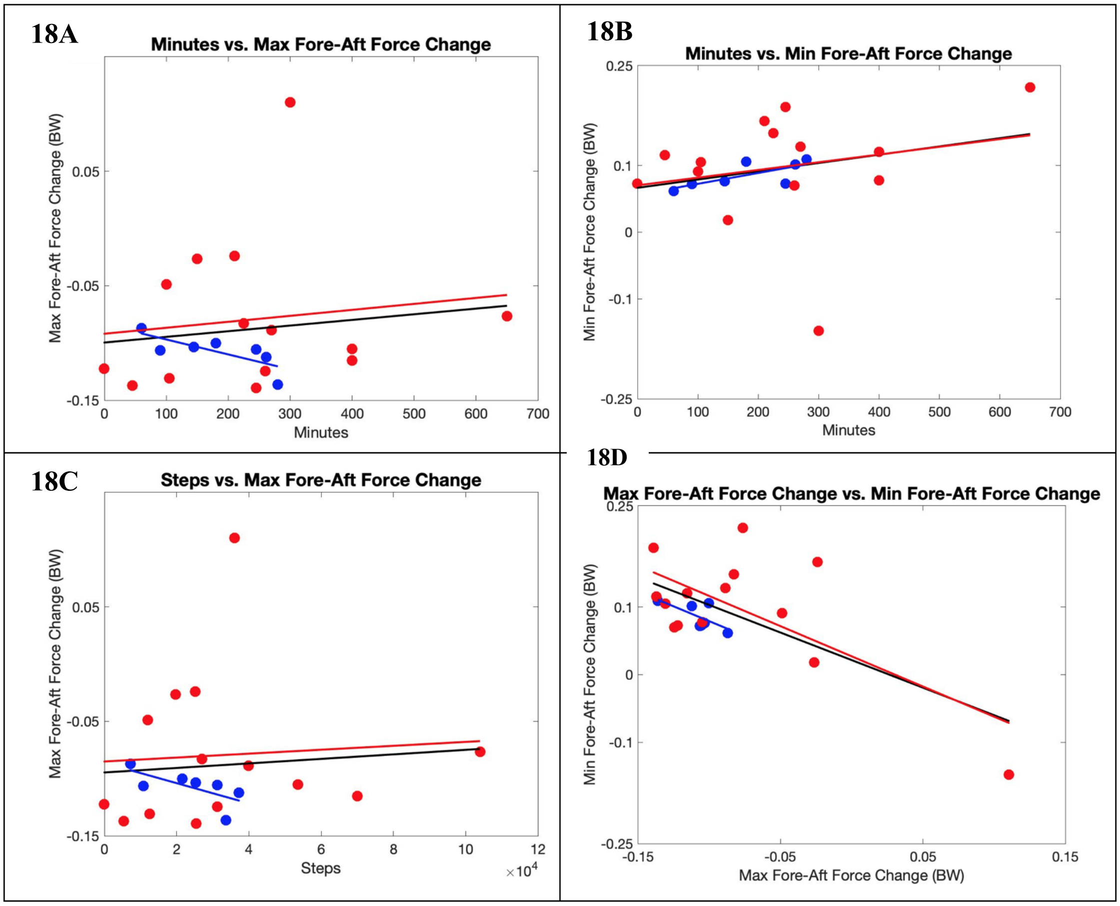

Figure 18: *Trends in magnitude for male subjects*. Male analyses are indicated by a blue line. **Figure 18A** and **Figure 18B** show trends with the independent variable, time (minutes) spent walking. **Figure 18C** and **Figure 18D** show trends between dependent variables with males.

Adaptation Strategy

For analyses with all subjects, there were no trends with independent variables. We did see a moderate positive trend with knee angle and step time asymmetry (0.3826, 0.0869). We also saw a trend between propulsive forces and braking forces (-0.4412, 0.1143) for female subjects. These trends are shown in **Figure 19A** and **Figure 19B**, respectively.

We did not find any trends between independent or dependent variables for male only analyses.

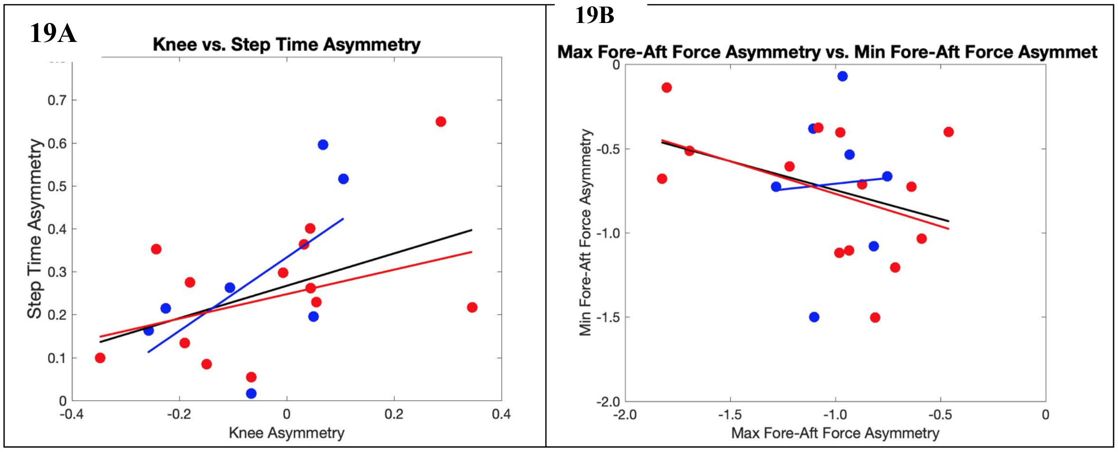

Figure 19: *Trends in strategy in all subjects*. Black lines indicate noteworthy trends for analyses considering all subjects. Trends here are between dependent variables. **Figure 19A** shows a positive trend with knee and step time asymmetry, and **Figure 19B** shows the relationship between propulsive forces and braking forces.

1-Process Timescales, Age

We found a moderate positive trend between age and step time asymmetry for washout of the dominant leg (0.5402, 0.0698), as seen in **Figure 20A**. When considering only male subjects, we found a positive trend between age and step time asymmetry between legs during adaptation (0.856, 0.0642), shown in **Figure 20B**. Additionally, we found negative trends age versus dominant ankle washout (-0.6784, 0.0939) in males, which is shown in **Figure 20C**.

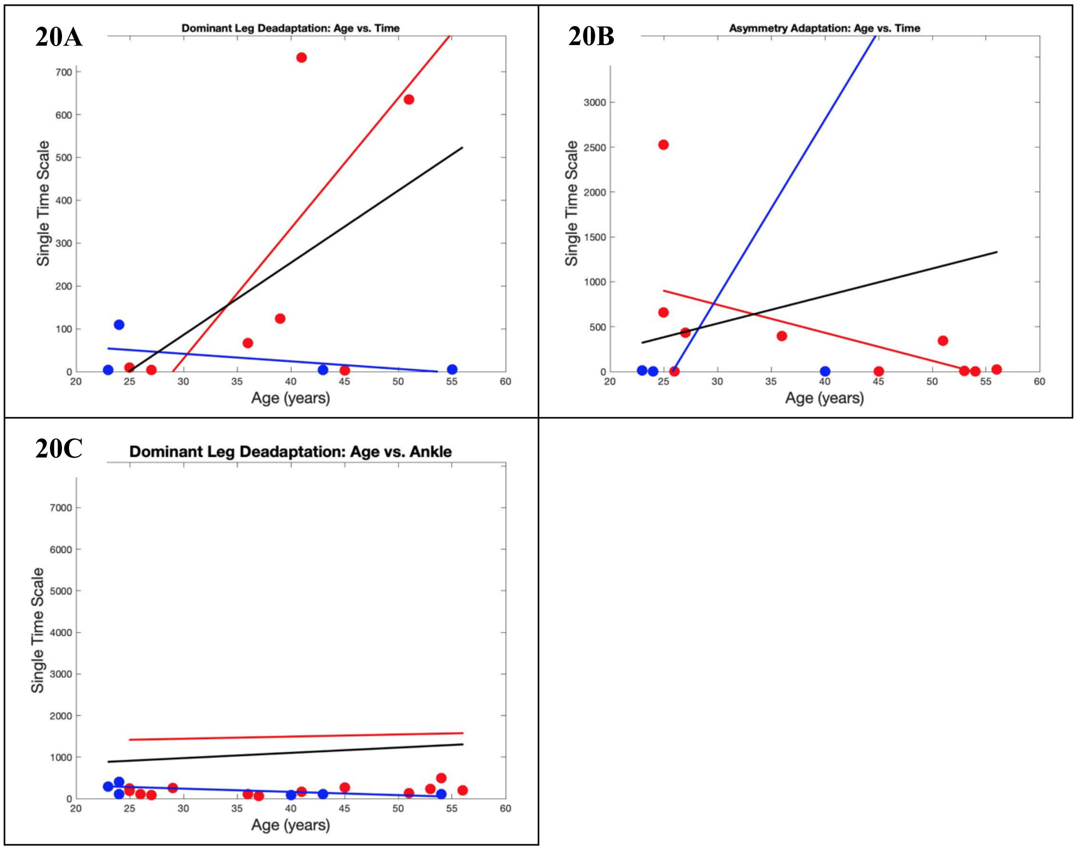

Figure 20: *1-process timescale trends with age*. **Figure 20A** shows a positive trend in analysis of all subjects. **Figures 20B** and **20C** are trends for analysis of males only, indicated by a blue line.

1-Process Timescales, Steps

We found a positive trend between steps taken and the vertical forces between legs during washout (0.6939, 0.0562). This trend is seen in **Figure 21A**. We also found a trend in steps taken versus step time asymmetry washout in the dominant leg (-0.906, 0.094) in male subjects only, as seen in **Figure 21B**.

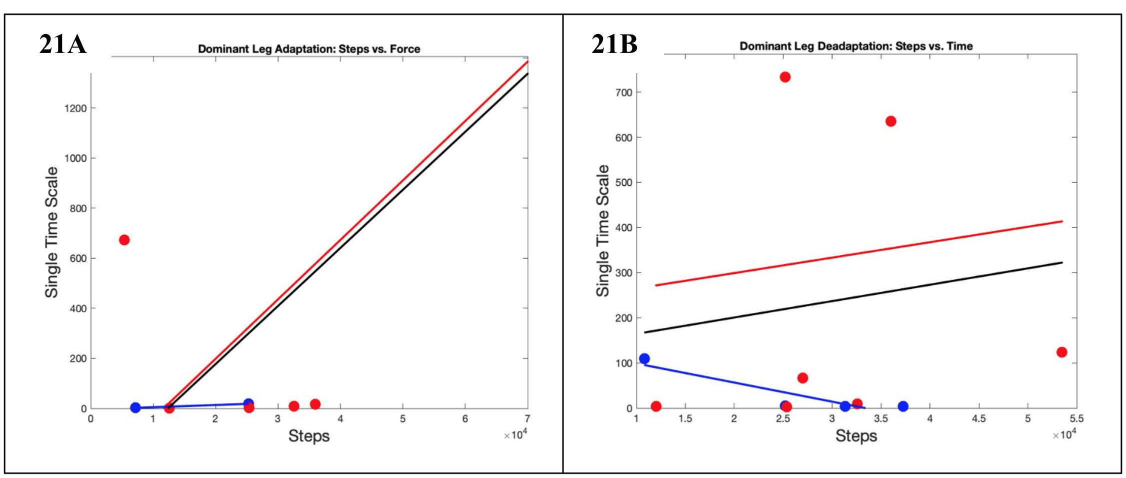

Figure 21: *1-Process Timescale trends with steps*. **Figure 21A** shows a positive trend in analysis of all subjects. **Figure 21B** is a negative trend for the analysis of only male participants, shown in blue.

Appendix C: Graphs for fore-aft force calculations during baseline, adaptation, and washout

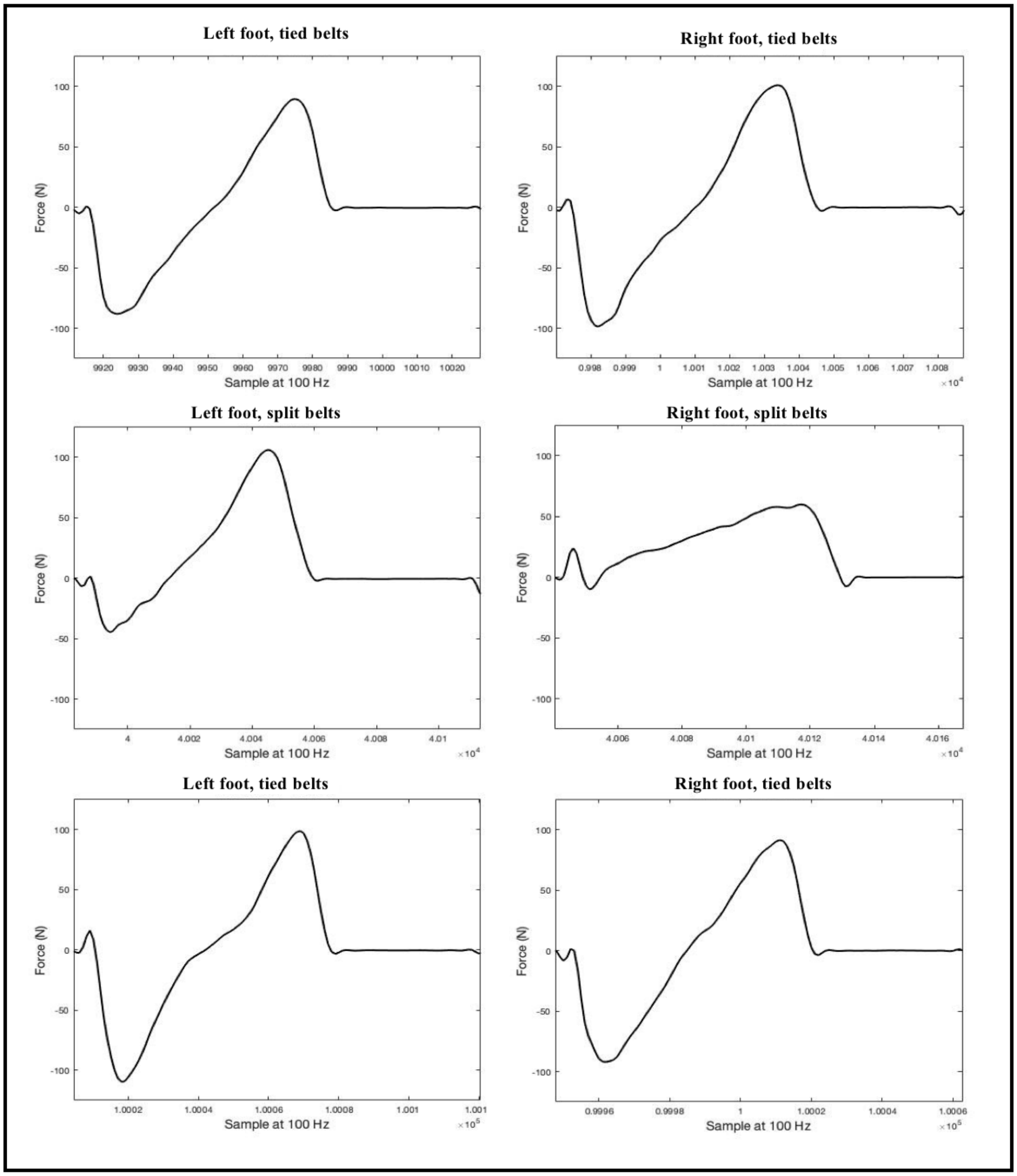

Figure 22: *Example fore-aft force graphs*. Graphs here are examples used for calculation of fore-aft forces. Minimum peaks were taken to be the braking force and maximum peaks were taken to be the propulsive force. From top to bottom, these graphs illustrate the three experimental phases: baseline, adaptation, and washout, respectively.

Appendix D: Participant Questionnaire

Post-experiment questionnaire
Complex walking tasks across ages

Investigator: Mark Osadjan, Dept. of Biology, Kristine Snyder, Dept. of Mathematics and Statistics

Subject Group: _______________

Subject Number: _________________________________

Occupation: _____________________________________

Birth Year: _______

Height: _______ Weight: ________

Current Weekly Exercise Habits:
Do you regularly engage in any of the following activities? If so, please indicate duration, frequency and intensity during a typical week. Please indicate if an activity is seasonal. For example: " I run 5 miles, 3 times per week at 7 minute per mile, during the summer months." or "I walk to school every day, about a mile, September through November." If you do not participate in an activity, please leave the space blank.

Duration Frequency
Intensity

Walking:

____

Running:

____

Biking:

____

Swimming:

____

Team sports:

____

Weight lifting:

____

Yoga:

Fitness classes:

Hiking:

Paddling:

Other (please describe):

To the best of your knowledge:

Are you in good general health?

Yes No

If no, please specify any known problems:

Do you have any difficulty with walking, running, or mobility in general?

yes or no

If yes, please specify: ____________________

Do you have any problem with balance or dizziness?

yes or no

If yes, please specify: ____________________

Have you ever experienced a serious musculoskeletal injury of your legs, feet or back?

yes or no

If yes, please briefly describe the nature of the injury and approximate date.

Do you currently have lingering symptoms or pain related to that injury (injuries)?

yes or no

If yes, please specify: ____

Have you ever experienced chest pain or shortness of breath with exertion?

yes or no

If yes, please specify: ____

Do you have hypertension (high blood pressure)?

yes or no

If yes, please specify: ____

Have you ever had a heart attack?

yes or no

If yes, please specify: ____

Appendix E: 2-Process Timescale Correlation Results

All results presented here rise to the level of statistical significance. These results are highly inconsistent in terms of the fit, therefore we focus on 1-process analyses in our discussion.

Table 3: *2-Process timescale results for analyses with all subjects.*

Independent Variable	**Dependent Variable**	**Quantity being measured**	**Correlation coefficient, p-value**
Age	Knee asymmetry between legs during adaptation	Fast timescale	(-0.8236, 0.0228)
Age	Knee asymmetry between legs during adaptation	Slow timescale	(-0.7668, 0.0443)
Age	Ankle asymmetry between legs during adaptation	Fast amplitude	(0.5573, 0.0132)
Age	Ankle asymmetry between legs during adaptation	Slow amplitude	(-0.5671, 0.0113)
Age	Propulsive force washout in dominant leg	Fast amplitude	(0.4341, 0.0493)
Age	Propulsive force washout in dominant leg	Slow amplitude	(-0.4341, 0.0493)
Steps taken	Ankle asymmetry between legs during washout	Fast amplitude	(0.782, 0.0002)

Steps taken	Ankle asymmetry between legs during washout	Slow amplitude	(-0.592, 0.0123)
Steps taken	Ankle asymmetry between legs during washout	Fast timescale	(0.7752, 0.0003)
Steps taken	Ankle asymmetry between legs during washout	Slow timescale	(0.774, 0.0003)
Steps taken	Braking force during adaptation in dominant leg	Slow timescale	(0.7235, 0.0001)
Steps taken	Step time during adaptation in dominant leg	Fast amplitude	(0.6268, 0.039)
Steps taken	Step time during adaptation in dominant leg	Slow amplitude	(-0.6268, 0.039)
Steps taken	Step time during adaptation in dominant leg	Slow timescale	(0.7804, 0.0046)
Steps taken	Vertical force asymmetry between legs during washout	Slow timescale	(0.7129, 0.0472)

Table 4: *2-process timescale results for analyses with females only.*

Independent variable	**Dependent variable**	**Quantity being measured**	**Correlation coefficient, p-value**

Age	Propulsive force washout in dominant leg	Fast amplitude	(0.6444, 0.0174)
Age	Propulsive force washout in dominant leg	Slow amplitude	(-0.6444, 0.0174)
Steps taken	Propulsive force asymmetry between legs during washout	Fast timescale	(0.6958, 0.0057)
Steps taken	Ankle asymmetry between legs during washout	Fast amplitude	(0.8061, 0.0049)
Steps taken	Ankle asymmetry between legs during washout	Slow amplitude	(-0.7079, 0.022)
Steps taken	Ankle asymmetry between legs during washout	Fast timescale	(0.8018, 0.0053)
Steps taken	Ankle asymmetry between legs during washout	Slow timescale	(0.8014, 0.0053)
Steps taken	Braking force adaptation in dominant leg	Slow timescale	(0.7384, 0.0017)
Steps taken	Step time adaptation in dominant leg	Fast timescale	(0.7876, 0.0355)

Table 5: *2-process timescale results for analyses with only males.*

Independent variable	Dependent variable	Quantity being measured	Correlation coefficient, p-value

Age	Braking force asymmetry between legs during washout	Slow timescale	(0.7641, 0.0273)
Age	Thigh angle asymmetry between legs during washout	Fast amplitude	(-0.7421, 0.035)
Age	Thigh angle asymmetry between legs during washout	Slow amplitude	(0.7421, 0.035)
Age	Braking force adaptation in dominant leg	Slow timescale	(0.7903, 0.0488)
Age	Braking force washout in dominant leg	Slow timescale	(0.8789, 0.004)
Age	Step time asymmetry between legs during washout	Slow amplitude	(0.8131, 0.0491)
Steps taken	Knee adaptation in dominant leg	Slow timescale	(-0.8773, 0.0217)
Steps taken	Vertical force during dominant leg washout	Fast amplitude	(-0.9998, 0.012)
Steps taken	Vertical force during dominant leg washout	Slow amplitude	(0.9998, 0.012)
Steps taken	Vertical force adaptation between legs	Slow timescale	(-0.8816, 0.0202)